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DNS for New Applications of Surface Textures and MEMS Actuators for Turbulent Boundary Layer Control - FINAL REPORT

GRANT NUMBER FA9550-05-1-0176

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Abstract

As a two year project related to our earlier AFOSR work, we examined the use of surface textures to suppress the growth of turbulent spots during the later stages of boundary layer transition. The textures are small and closely spaced and hence require detailed direct numerical simulation of the near surface flow to capture the physics. The work emphasized the fundamental nature of that flow/texture interaction. This project primarily involved the application of our pre-existing computational techniques and software but did require the alteration of the code to handle a boundary layer and to run with high spatial resolution on a parallel processor. The possible applications to boundary layer control are suggested in **Background** while the section called **Proposal Objectives** reviews the approaches considered. Finally, an attached **Detailed Report** is a comprehensive discussion of previous scientific work, our techniques, and our results.

Background:

Boundary Layer Transition: A greater knowledge of turbulent boundary layer structure and development and the creation of means for boundary layer transition control are essential to several applications in the fields of aerodynamics. As Tollmien-Schlichting waves in a laminar boundary layer grow to develop unstable 3D perturbations, turbulent spots form. In an uncontrolled flat plate boundary layer, such arrowhead-shaped spots appear at randomly distributed points and their growth and merging lead to complete transition to turbulence. A spot appears as a fairly well defined region of turbulence surrounded by laminar flow. Wignanski *et al* [1], performed detailed experimental studies of such spots and Leonard [2] briefly reviewed some of the first simulations with vortex methods of a spot-like perturbation in a laminar flow. Spots have been successfully simulated in several shear flows (e.g., [3]). Spots appear to displace some near-wall fluid outward (a spanwise velocity component) and produce spanwise traveling waves [4].

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Often, flow conditions are not sufficiently perfect that transition occurs in the classic 2D TS instability \rightarrow 3D perturbation growth \rightarrow turbulent spot progression. For example, roughness elements (e.g., bugs) can cause a premature immediate bypass transition to turbulence in a wedge-like region aft of the perturbation. (Although this situation might be conjectured to be just a continuous sequence of spots.) Joslin [5] particularly points out the detrimental effects of leading edge contamination for laminar flow control. A turbulent boundary layer is characterized by swirling, unsteady, seemingly random motion. In fact, however, the motion is not random but may be organized into a variety of quasi-periodic vortical structures. These vortices lead to the formation of low speed streaks which are believed to be responsible for the breakdown and eruption of the wall layer, a key mechanism in the production of new vortical structures and the increase in shear stress at the wall. We note that in both the formation of turbulent spots and wedges, the near-wall turbulent structures of streamwise vortices and hairpins appear much like those in a fully developed turbulent boundary layer. In fact, the lateral spread with downstream propagation distance of those spots/wedges appears related to those same fundamental structures.

If one can delay or confine the regions of laminar to turbulent transition, the benefits could be appreciable. For example, since the viscous drag of a turbulent boundary layer can be four or more times greater than that of a laminar layer, one can imagine that sufficiently delaying transition could lead to greater aircraft loiter times over targets or a decrease in the need for in-flight refueling. It has been found experimentally, as reviewed in [6] and [7], that passive surface textures, *e.g.* streamwise riblets, can reduce the *turbulent* drag on a surface by five to ten percent. We have confirmed this numerically and have shown that riblets work by damping the near-wall spanwise fluctuations [8,9]. However, we are unaware of recent efforts to control or constrain the lateral spread of the late stages of natural or bypass transition by such passive texturing. We saw a unique opportunity here: surface textures like riblets have not seen wide application due to their relatively modest benefits in reducing turbulent drag (compared to their weight, installation and maintenance costs, etc.). Locally, however, where the flow is transitioning, there is such a large change in surface shear stress that riblets might find use if they can be optimized to delay or constrain such transition.

The Force Field Model and Spectral Approach: There exist several approaches to simulating turbulent boundary layers over textured surfaces. We have published a method for modeling a variety of surfaces in a spectral method simulation [8,9,10]. Our approach is particularly flexible and has been successfully tested on a range of turbulent flow configurations over riblets and MEMS-like devices. In a spectral method, the spatial distribution of the dependent parameters (velocity, vorticity, pressure, *etc.*) is commonly modeled with Fourier and Chebychev series in a simple domain. Part of the computation is performed on the parameters themselves and part on the Fourier and Chebychev coefficients of the parameters. Efficient transform methods are used to move between the real and spectral representations. The spectral code we use is based on the method in [11] (also described in [12]).

The geometry of interest here is that of a developing boundary layer in which the wall has an array of riblets or fins. The spatial development in the normally homogeneous direction is modeled, as in Goldstein *et al* [13], via an absorbing buffer layer. Our technique for modeling the virtual surface introduces a localized body force field into the Navier Stokes equations.

Such an approach has been used in many other applications, particularly by Peskin [14] and later co-workers, and some of that literature was briefly summarized in [8] and [13]. Several groups at the AFOSR LES-DNS Summer 2001 meeting discussed related approaches. Our force field is made to adapt to the flow and bring it to a specified velocity on the intended boundary points thereby creating a virtual (stationary or moving) solid surface. The force is computed by a feedback scheme in which the velocity is used to iteratively determine the desired force field. The stability of our approach, in particular, has now been investigated in detail by Lee [15]. Our force field technique allows us to utilize the fast transform methods without encountering the severe limitations of a simple geometric domain imposed by most other spectral approaches.

This virtual surface model has been used to simulate the flow around moving boundaries, vortex shedding off of circular cylinders [10] and cubic obstacles, the turbulent flow over flat and riblet covered surfaces [8,9], arrays of wires parallel to an underlying flat surface [8], arrays of linear microjets under turbulent boundary layers [16], and surfaces having three dimensional waves. Our simulations of turbulent flow over flat plates and riblets have been validated in detail against both experiments and other workers' simulations. The key results from the riblet work related to the present effort are that riblets reduce drag by damping the cross-flow fluctuations near the riblet crests, that some riblets cause slugs of near-wall enstrophy to ride along the rib crests parallel to the mean local flow, and that riblets can turn the near-wall flow to more nearly follow the riblet crests.

Proposal Objectives: Surface Textures to Control the Growth of Spots

I proposed to continue to use our CFD approach to investigate the use of surface textures to constrain the development of local turbulent regions. As a turbulent spot moves downstream, it spreads laterally until it merges with other growing spots and the entire span becomes turbulent. Although the spots themselves have an interesting structure, they appear much like small arrowhead-shaped regions of fairly developed turbulence and so might be subject to means of control already developed for a fully turbulent boundary layer. Although the development of spots may be unavoidable, perhaps their growth can be constrained by a riblet covered surface. So even though having riblets or other textures covering much of an aircraft surface does not usually pay off, riblets applied locally to extend the end of the laminar region have greater potential leverage since there is such a large increase in shear stress in a turbulent flow and since small areas of riblets are cheap.

Figure 1 indicates a schematic idea of the problem. We can run laminar flow over a surface covered with riblets and momentarily introduce a localized perturbation to induce turbulent spots. We use a buffer (fringe) region to study spatially developing flows and this requires a large domain. We then simulate spot growth and development over ribbed and smooth surfaces to investigate the differences. We have examined questions such as: Do the spots grow at the same rates over different surfaces? Do they move at the same speed? How are the internal structures of spots altered by the surface texture? What are optimal riblet shapes? Do riblets, in fact, promote the growth of some 3D instabilities? (Presumably large enough riblets do.) Can riblets constrain the spreading angle of the spots? Can riblets

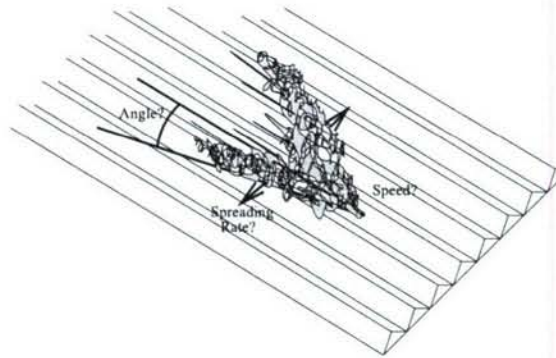


Figure 1: Schematic showing a turbulent spot aft of a perturbation moving over riblets.

usefully change the recovery to laminar flow in the wake of the spots?

Our initial task was to bring the new student up to speed with our existing software. He was then to examine, separately, baseline cases of turbulent and laminar flow in a simple channel and over riblets. He would then introduce a perturbation in a laminar Poiseuille flow and compare to previous turbulent spot simulations. Finally, he would perturb laminar flow over riblets. The results are presented in an attached detailed report. During the course of the project, one US graduate student was supported as well as two US undergraduates (both of whom have now gone on to graduate school). One AIAA conference paper, three technical reports and one MS thesis were produced. One journal publication is soon to be submitted. The graduate student spent two weeks at the Navy Research Lab in Washington learning about the spectral code and has now completed his oral and written PhD qualifier exams. Related work is continuing under a follow-on AFOSR grant.

Detailed Report:

See attached.

References

- [1] J. Wygnanski, M. Sokolov and D. Friedman, 1976, "On a turbulent "spot" in a laminar boundary layer," *J. Fluid Mechanics*, **78**, 785-819.
- [2] A. Leonard, 1985, "Computing three-dimensional incompressible flows with vortex elements," *Ann. Rev. Fluid Mech.*, **17**, 523-559.
- [3] B. Singer and R. Joslin, 1994, "Metamorphosis of a Hairpin Vortex into a Young Turbulent Spot," *Phys. of Fluids*, **6**, no. 11, Nov. 3724-3736.
- [4] N. Tillmark, 1995, "On the spreading mechanisms of a turbulent spot in a plane Couette flow," *Europhys. Lett*, **32**, 481-485.
- [5] R. Joslin, 1998, "Aircraft laminar flow control," *Ann. Rev. Fluid Mech.*, **30**, 1-29.

- [6] M. J. Walsh, 1990, "Riblets." In *Viscous Drag Reduction in Boundary Layers*, ed. D. Bushnell and J. Hefner, Progress in Astronautics and Aeronautics, v. 123, p. 203-259, AIAA Washington, DC.
- [7] E. Coustols and A. M. Savill, 1992, "Turbulent skin-friction drag reduction by active and passive means: parts 1 and 2," Special course on skin-friction drag reduction, p. 8-1 to 8-55, March 2-6, in AGARD Report 786.
- [8] D. B. Goldstein, R. Handler, and L. Sirovich, 1995, "Direct numerical simulation of turbulent flow over a modeled riblet covered surface," *J. Fluid Mech.*, **302**, Nov. 10, 333-376.
- [9] D. B. Goldstein and T.-C. Tuan, 1996, "Secondary flow induced by riblets," *J. Fluid Mech.*, **363**, pp. 115-151.
- [10] D. B. Goldstein, R. Handler, and L. Sirovich, 1993, "Modeling a no-slip flow boundary with an external force field," *J. Comp. Phys.*, **105**, pp. 354-366.
- [11] J. Kim, P. Moin, and R. Moser, 1987, "Turbulence statistics in fully developed channel flow at low Reynolds number," *J. Fluid Mech.*, **177**, 133.
- [12] R. A. Handler, E. W. Hendricks, and R. I. Leighton, 1989, Low Reynolds Number Calculation of Turbulent Channel Flow: A General Discussion. NRL Memorandum Report 6410, p. 1-103.
- [13] D. Goldstein, J. Cohen and V. Levinski, 2001, "DNS of Hairpin Vortex Formation in Poiseuille Flow Due to Two-hole Suction," presented at 3rd AFOSR Int. Conf. on DNS and LES, Arlington, TX, Aug..
- [14] C. S. Peskin, 1972, "Flow patterns around heart valves: a numerical method," *J. Comp. Phys.*, **10**, 252-271.
- [15] C. Lee, "Stability Characteristics of the Virtual Boundary Method in Three-Dimensional Applications", 2003, *J. of Computational Physics*, Vol. 184, pp.559-591.
- [16] T.-C. Tuan and D. B. Goldstein, 1996, "Direct numerical simulation of arrays of microjets to manipulate near wall turbulence," U. T. Austin Center for Aeromechanics Research Report CAR-96-3